A Geographic Information System (GIS) for Explosives Facility Siting Analysis

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Abstract

Barricades, related facilities, segmented clear zones, waivers, and exemptions are just some of the problems faced daily by explosives siting analysts. The number of explosives locations in close proximity to operational and support facilities makes site selection one of the most critical issues relating to explosives safety. Yet, there is seldom time using conventional methods to examine all of the relevant options.

The use of Geographic Information Systems (GIS) has grown substantially in the last several years as the technology has matured to the point where it is relatively user-friendly, affordable, and accessible. The application of a GIS to the problem of explosives facility siting analysis has resulted in increased productivity, decreased errors, and the ability to detect problems that humans alone might overlook.

Introduction

Anyone who has attempted to analyze a site plan with a ruler and a calculator can testify that it is a process which begs to be automated. Not only is it tedious and error prone, but often the entire process must be repeated when the slightest change is introduced. Additionally, there is paperwork to type and revise with endless columns of figures that must be checked and rechecked. Many would agree that it is a task for which the computer is well suited. The question is how should it be applied?

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The Air Force Explosives Hazard Reduction (EHR) Program Office at Eglin AFB, FL has been tasked to perform an EHR survey of several US overseas bases, the majority of the work to be performed by a small team of contractors from ISA with experience in explosives siting. Because of the magnitude of the effort and the pace of the schedule, the team also included a programmer to automate as much of the task as possible. The first EHR survey was recently completed, and the results of the experience and some of the lessons learned are presented herein.

The purpose of the EHR survey is to:

- Identify and quantify threats and operational restrictions posed by the presence of our own munitions stocks.
- Provide recommended approaches to reduce or mitigate these threats and restrictions.
- Recommend initiatives for inclusion in the EHR program.

Because ISA was not tasked to develop hardware or software systems for general use, tools and systems were applied that were on hand at the time. Other systems were not considered because of the time and expense of acquisition and training. Accordingly, these discussions will be presented in as general terms as possible so as to benefit those with different requirements. It should be emphasized that this was not a normal life cycle software development project taking years, but an on-the-fly effort where the software necessary to perform a certain task was usually started and finished on the day before it was needed. This quick turnaround sometimes led to false starts and blind alleys, but also to a kind of synergism between user and programmer that resulted in innovative solutions to complex problems. It also led to the realization that it takes less effort to automate many tasks than it normally takes to perform them even once.

Background

A GIS is an information system that is designed to work with geographically referenced data. It can be thought of as a higher order map which includes both a spatially referenced database and a set of operations for manipulating it at computer speeds.

The target hardware was an Apple® Macintosh™ running a MapGrafix™ computer-aided mapping system linked to a 4th Dimension™ database. The team utilized four Macintosh™ computers ranging from the SE to the IIfx. All

were equipped with large screen monitors to facilitate working with maps and large spreadsheets of data. Output devices included an "E"-size HP pen plotter, three laser printers and a small portable ink-jet printer for field operations. Paper maps were digitized with the aid of a Kurta "E"-size digitizing tablet.

Custom programming was added to MapGrafix™ in the Pascal language and to 4th Dimension™ in its scripting language. Over an eight month period approximately 10,000 lines of code were written to enhance and customize the GIS, and another 5,000 were written for the database.

The Pascal code automates the process of digitizing base maps by providing templates for standard explosives enclosures and other facilities. It can automatically produce a report with the distances and exposures between every potential explosion site (PES) and all respective exposed sites (ES) within a user defined distance. If barricades have been digitized, the report will also show if a particular building pair is barricaded or not, and notes the identifiers (IDs) of the barricades involved.

The database code streamlines the data entry of information pertaining to individual base facilities, waivers and exemptions, and separation criteria tables. It automates the calculation of quantity distance (QD) and provides searches for finding the problem facilities. Information is output to the map which automatically creates clear zones around the selected facilities. Lists of building pair (PES-ES) data can be exported for inclusion in reports, and AF Form 943's can be printed on a laser printer. The system can also generate an assessment of risk to each facility from all nearby potential explosion sites. The risk assessment, at this point, is based on computed separation factor and a table of estimated damage by structure type. The computed separation factor is given by the distance between the PES and the ES divided by the sited net explosive weight (NEW) raised to the one third power.

Computerization

All tasks performed with the aid of a computer can be divided into three stages: input, process, and output. Input or data entry, in this context, is an extremely technical process which requires knowledge and experience relating to explosives siting. The old saying, "Garbage in, garbage out" applies, and only careful attention to detail can prevent small errors from being magnified by the computer. The team found a small, but significant number of errors in the source data which could be located by cross referencing and looking for inconsistencies.

Processing is the part where all of the data has been input and automatic algorithms are being applied to produce results. Processing, usually the smallest portion of the task, is the most exciting part, since after weeks of entering and cross checking data, you can sit back for a few hours while the computer does all the work for you. This is what the general public thinks of when they think of data processing. Perhaps it is because of those early cartoons that depicted men in white lab coats with their feet up on desks in front of a giant mainframe, and a sign that reads "don't bother to think."

Output, of course, is traditionally the part where the computer produces reams of paper copy which is printed in neat rows and columns, bundled into boxes, delivered to the customer, and stored in some closet never to be seen again. For this reason, there is usually some kind of post-processing designed to reduce the results down and summarize them into some form with which humans can cope.

Collecting the Data

The first step in computerized site plan analysis is data collection. In our case it involved obtaining paper copies of base maps at a scale of 1:600 (1"=50') and 1:5000 (1"=416'). Copies of facilities development plans for future construction and five year capital improvement programs were also obtained. In addition we acquired lists and locations for electro-magnetic radiation hazards, explosive safety quantity-distance maps, and aircraft parking maps. In order to classify and compute QD for each facility we requested and received listings of the real property inventory detail lists, facility data records from munitions branch CAS-B records, and copies of all current and pending site plans, exemptions, waivers, and deviations. Other data of interest include: "As Built" drawings, bench mark coordinates, USAF Definitive Drawings, drawings identifying barricades by type, and a regional location map.

All totalled, this can amount to some thirty pounds of paper which must be forced into the computer against its will. Right about now, some people usually ask why this mountain of information can't be provided in electronic form. These are usually people who have never been involved with transferring information from one computer system to another. Here is a somewhat facetious test to illustrate the point. Suppose you call the safety office at the base you are about to survey and ask for all of the above information in electronic form, will the person on the other end of the line be more likely to: A) Ask what format diskettes would you like that on? B) Request a stock number. Or C)

laugh in your face. If you answered B or C, you have your feet firmly planted on the ground. If you answered A you may have a problem distinguishing reality and should consider a career in politics.

Digitizing the Maps

When some people hear the phrase "digitizing maps", they think that we are talking about scanning with a flat-bed or sheet-feeding scanner because that has become a relatively common process due to desk-top-publishing. What we are really talking about though, is taping the paper maps to what looks like a large draftsman's table and clicking on the endpoints of lines with a small hand held puck equipped with cross hairs. It is a process similar to solving a child's puzzle called connect-the-dots. This is the normal method in the GIS world, but it is seldom seen outside of it, and as a result outsiders are somewhat confused by it. They are often appalled by its labor intensive nature and the fact that it seems like a low-tech solution. The situation is complicated by the fact that there are now services to which you can send your maps, and they will be scanned and "auto-traced." If you do your furniture shopping at K-Mart, you will probably be really happy with an auto-traced map, because when you pick it up, you find that you still have to put it together.

Since one of the goals of the system is to automatically determine the orientation and exposures of PES to ES pairs, buildings must be digitized in a specific way. Buildings are entered as a series of corner points with lines connecting them for walls. We arbitrarily chose to enter them in clockwise order with the front left corner entered first. This is important since the blast and fragment hazard is different for the front, side, and rear of many explosives facilities. All of the standard building types are entered with a computerized template mechanism that ensures that they are drawn in a consistent manner that the computer can later break apart into component pieces of front, side, rear, door, blast deflector, and so on. As a part of the process, the buildings are given IDs which serve as the computer's link between the database and the drawing.

Creating the Database

There are four files of data that must be set up before the automated analysis process can begin. They are the facility file, the facility type file, the separation criteria file, and the waivers and exemptions file. The facility file contains all of the information about a particular facility referenced by building

number, and is entered from scratch for each base surveyed. The facility type file contains a list of building types organized by categories, and may require updating to include local facility types not previously encountered. The separation criteria file is a table organized in rows and columns containing a separation factor and minimum distance entry from every PES facility type to every facility type. Its current size is around 12,000 entries, but it is expected to grow to around 30,000. The waivers and exemptions file contains a list of potential explosion sources and exposures affected by the waiver or exemption. A database might contain as much as 20,000 kilobytes (20 MB) of data.

Turning the Crank

Once the data has been collected and entered and the maps have been digitized and linked with the database, we can finally make the computer begin to pay for itself by applying algorithms to the data to automate the processes that were formerly done by hand. These algorithms are the real focus of this paper, since without them the GIS system would be only marginally useful. Therefore, it is necessary to examine them in some detail, and in somewhat technical language.

We begin with the fundamental problem of determining the distance between two facilities. Since the Greeks, it has been known that the distance between two points P_0 and P_1 in the Cartesian plane is given by:

Formula 1. $$d = \sqrt{(X_1 - X_0)^2 + (Y_1 - Y_0)^2}$$

However, representing buildings as points does not yield the required accuracy for explosives site planning purposes. We must instead represent them as the line segments between the corner points of the outer walls. This implies there are an infinite number of distances between two buildings depending on where you measure. In the simplest case, we are only interested in the shortest distance since that will be the one which drives our requirements. A little thought will convince you that the shortest distance (or equal in the case of parallel walls) is always between a corner point of one building and a point on the wall of the other building. So if we have a formula to find the distance between a point and an line segment, we can simply take the minimum of all the distances between all of the corners in one building and all of the walls in the other and vice versa. Since we are dealing with line segments and not lines, we must use parametric equations.

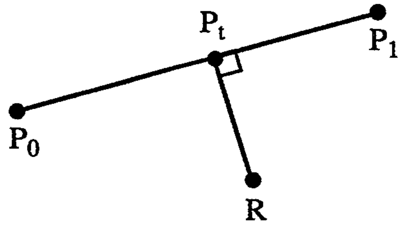

Figure 1.

The parametric affine equation of a line is given by:

Formula 2. $P_t = P_0 + t\,v$

Where **v** is the vector from P_0 to P_1, R is a point not on the line, and **t** is a parameter which varies from 0 to 1. Since the minimum distance occurs where the line from R to P_t is perpendicular to v, we can set the dot products of the two vectors equal to zero and solve for **t**.

Formula 3. $t = \dfrac{(R - P_0) \bullet v}{v \bullet v}$

If **t** is in the interval 0 to 1 then the perpendicular intersects the line segment and we can plug **t** back into Formula 2, solve for P_t and the distance is then given by $|R - P_t|$. On the other hand, if **t** is negative, the distance is $|R - P_0|$, and if **t** is greater than one, the distance is $|R - P_1|$.

The problem of finding distances between buildings is further complicated when one or both of the structures has a segmented clear zone. Segmented clear zones are the result of structural differences between the front, side, and rear of explosives enclosures. Explosives siting criteria, therefore, distinguishes between the required inhabited building distance (IBD) for a standard igloo, for example, by orientation, with the front sector being the most restrictive. This will be discussed in more detail later in the paper.

The parametric affine equation of a line is also useful for solving the problem of the intersection of two line segments. This is necessary when determining if a barricade falls between two buildings, and is also used for clipping a polygon to remove the portion falling on one side of a line. (Polygon clipping is a problem which occurs in computer graphics and detailed algorithms can be found in the textbooks of that field.) *Figure 2* shows the intersection of two line segments at a point P_t which is unknown:

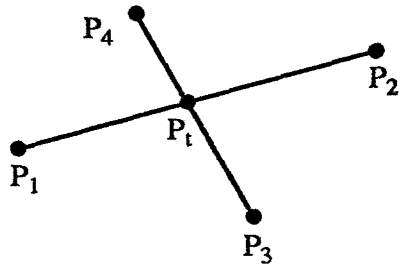

Figure 2.

Formula 4.1 $P_t = P_1 + tv$

Formula 4.2 $P_s = P_3 + sw$

Where v is the vector from P_1 to P_2, w is the vector from P_3 to P_4, and s and t are parameters which vary from 0 to 1. Since P_s and P_t are equal at the point of intersection, we can break the two vector equations into their scalar components and solve simultaneous eqations to eliminate the unknown in s giving:

Formula 4.3 $$t = \frac{Y_w(X_3-Y_1)-Y_w(Y_3-Y_1)}{Y_wX_v-X_wY_v}$$

Where the subscripts indicate from which vector or point (points are considered position vectors) the scalar components were derived. We then apply t to *Formula 4.1* to give the point of intersection. Astute readers will have noticed that the denominator of *Formula 4.3* is the determinant of the matrix of v and w corresponding to the vector cross product, and is zero only when the two are parallel. This must be checked first before applying the division.

Applying the Math

Armed with these two simple procedures for determining distance and intersection, we are now able to take on the task of determining the distances between two buildings with segmented clear zones and possible barricades in between. In contrast with the relatively simple mathematics presented above, the water now gets both deeper and murkier.

A simple case involving a segmented clear zone is illustrated below involving a hardened aircraft shelter (HAS) and another building. The HAS projects a clear zone in a 30° cone coming out of the front with the vertex placed so that the sides of the angles pass through the intersection of the door and side walls. Since the side of the cone passes through other building, there is both a front and side exposure, and we need to measure the distance of both.

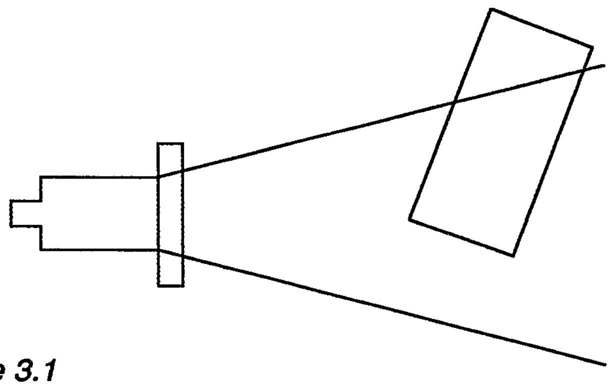

Figure 3.1

This is most easily accomplished by slicing the exposed building into two parts and applying our procedure for computing distances to each of the respective parts in turn. The distance measured from the front of the HAS is:

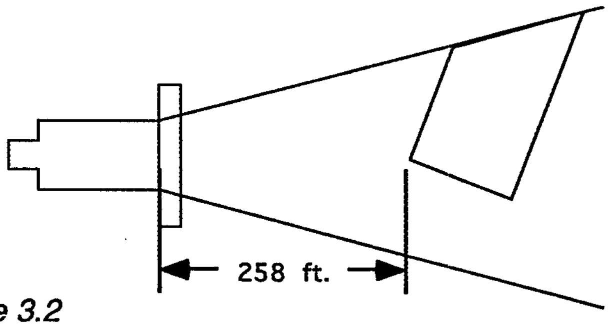

Figure 3.2

The distance measured from the side of the HAS is:

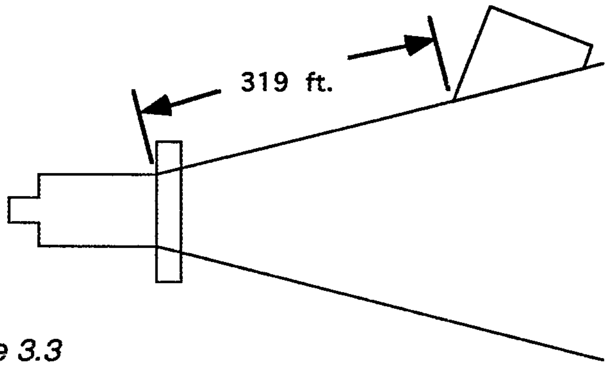

Figure 3.3

In order to go about slicing (or clipping) an arbitrary closed polygon with a line we must first develop a method for determining if a point is to the left or right of a vector.

Given two points P_0, P_1, and a point R just as in *Figure 2* we begin with the following general equation of a line:

Formula 5 $aY - bX - c = 0$
where $a = X_1 - X_0$, $b = Y_1 - Y_0$, and $c = aY_0 - bX_0$

Changing to inequalities, we find that $aY_R - bX_R - c < 0$ when the point R is to the right and > 0 when it is to the left (where left and right are as if you were standing on point P_0 looking toward P_1.) Of course, if $aY_R - bX_R - c = 0$ the point is on the line.

Clipping then, involves considering each point of the polygon in turn, keeping it if it is on the side we want, and removing it if not. Each time that we change from one side of the clip line to the other, we must compute the intersection of the current polygon side with the clip line, and retain that point.

Finding Barricades

Given that we have two buildings represented by polygons, we add a third polygon, possibly between the two, possibly not, which will represent a barricade. We wish to determine if any point on building A can connect to any point on building B without intersecting a barricade wall. While a general solution to this problem is not known to me, a rough approximation that works in almost all real world cases is as follows: Apply the intersection test to each line joining the corner points of A with the corner points of B, and every barricade wall. If any line fails to intersect at least one barricade wall, then the barricade does not completely protect A from B or vice versa.

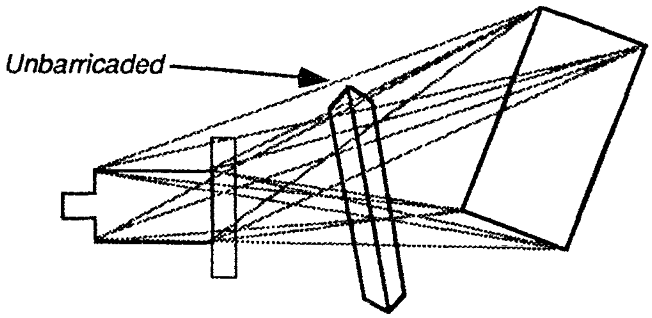

Figure 4

This procedure can be extended easily to handle multiple barricades, but it should be noted that limits must be placed on the distance that a barricade can be from a PES or ES because the effectiveness of a barricade diminishes rapidly with distance. The method can sometimes fail to detect small openings between multiple barricades. However, since that would constitute a design flaw in the barricade, it is assumed to be a rare occurrence. Barricade detection can add significantly to the processing time, since where there is one barricade, there are usually several hundred. Unless some optimization is applied to the process, it can easily take days of computer time. One optimization would be to keep list of barricades that are near enough to each building to be considered a candidate.

There are cases where we wish to know if one particular side of a building is barricaded, rather than considering the building as a whole. These are the same buildings that have segmented clear zones and require separate distance measurements, and so are handled by the same method of clipping the exposed building to the required arc and running the barricade test on the remaining portion.

Determining Exposure Faces

US Department of Defense Standard 6055.9 chapter 10, paragraph C2 states that *"A particular face of an ES is deemed to be threatened by a PES face when both of these faces lie within the arc of the threat or hazard of the other."* Figure 5 shows two standard earth-covered magazines (igloos) whose front faces do not lie within the 120° front cones of the other, but which will have front distances output by our compute distance procedure, since some of the building will lie within the cone.

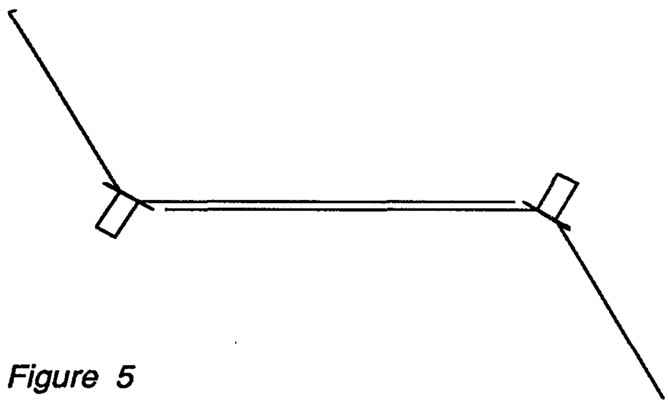

Figure 5

What is needed is to enhance our compute distance procedure for segmented clear zones to determine which faces are exposed, if the other building also has a segmented clear zone. Then we must compute the distances and exposed faces from the other building back to the first and eliminate distances to faces not within the arc of the other.

Determining which faces are exposed can be accomplished fairly easily for buildings that have a convex shape; that is, any building whose sides never face each other. After computing the distance from a particular segmented clear zone sector, we take the remaining part of the exposed building that lies within its arc and consider it one wall at a time. Beginning with the front wall and going clockwise around the structure, (since that is how we have standardized our digitizing process) we apply the procedure for determining if a point is to the left of a line. If either of the two endpoints of the source wall of the PES are to the left of the ES front wall (standing at the front left corner and looking along the door), then the source wall can be seen from the exposed wall, and the ES side is therefore considered an exposed face. The process continues around the ES until all sides have been considered.

After this process has been applied for each sector of the PES, and the ES faces exposed to each have been recorded, the roles of the PES and ES are reversed and the process is repeated until the exposed faces of each have been determined. Both lists are then checked against the other to eliminate distances to exposed faces that do not lie within the arc of the threat of the other.

It should be noted that all of the above algorithms have been simplified to the point where it is possible to explain them in simple English, and much work is needed to convert them into working procedures in any computer language. For instance, we have ignored the fact that the threat arc for the front of a hardened aircraft shelter is different when it is considered as a PES from what it is considered as an ES.

Priming the Database

After determining the distances and exposures, and noting the presence of barricades between each PES/ES pair, we then consider how this information can be processed for use in the explosives site planning analysis. One of the obstacles to the process is the problem of information overload. The computer obediently produces tens of thousands of lines of output which we must sort through to find the (hopefully) few hundred cases in which we are interested. Accordingly, the first step in analyzing our initial output is to transfer it to a database program.

In this process, data generated from the map is combined with data from other files to create records which completely describe the relationship between the building pairs. As the data is read into the **PES/ES** database file, the facility number of each is checked against the previously entered **Facility** file and the **Facility Type** of each is noted. The PES and ES Facility Types are used as indexes for the row and column of a table called the **Separation Criteria** file which contains the quantity-distance criteria derived from US Air Force and DoD standards. The table contains the **Separation Factor** (K-Factor or Q-Factor) for hazard class/division 1.1 munitions, the minimum allowable distance, and a field which contains note numbers of notes which detail exceptions and amplifications for this particular type pair. Note numbers are prefixed by a plus (+) sign if the note contains information which could result in the Separation Factor being increased or the minimum distance being decreased. The file contains separate entries for barricaded and unbarricaded building pair types. The Separation Criteria file is further broken out by exposure if a particular Facility Type has different criteria for each side.

Once we have the Separation Factor and minimum required distance, we can compute the factors which are the heart of our analytic capability, **Required Distance** and **Maximum Allowable NEW**. We use the formula: distance equals Separation Factor times Net Explosive Weight raised to the one third power. This formula gives the required separation distance for a particular Separation Factor and explosive weight. We also compute the maximum allowable NEW for a given actual distance and Separation Factor by the formula: NEW equals Actual Distance divided by the Separation Factor the quantity cubed. For multiple exposures, we compute the results of all, and use the most restrictive. In other words, we use the maximum allowable NEW which is smallest, or the required distance which is largest. It should be noted that the procedure is slightly more complex when dealing with so-called **Incremental Distance** criteria which are not smooth exponential curves, but the result is the same.

After computing the maximum allowable NEW and required distance, we must check to see if the actual distance is less than the required minimum distance. If it is, the maximum allowable NEW is set to zero, meaning that if the two building do not meet minimum separation requirements, then you cannot store explosives in the PES. If the actual distance is greater than or equal to the required minimum, and there is no Separation Factor criteria in the table (represented by a zero value), then a maximum allowable NEW by type is used from the Facility Type file.

The maximum allowable NEW that has been computed thus far applies to only one PES/ES pair. In order to find the true maximum for a particular PES, we must examine the maximums to each of the exposed sites, and take the smallest value. The facility number of the ES which yielded the smallest maximum allowable NEW is noted in the PES Facility record as the **Limiting Factor**. This information can be useful when we are seeking solutions to criteria violations.

Sorting out the Problems

The actual computerized analysis begins with a **Multi-Problem Facility Search.** This is a search applied to the entire database which produces a list of facilities that cause a criteria violation for more than one PES. This allows the analysts to concentrate their efforts on the worst problems first. On the initial run, it will often reveal data entry errors and problems with the criteria data or how it is applied, as well as legitimate violations. The results of the search can be output as a PES/ES building pair list sorted by ES so that you can go down the list and quickly determine what the problem is.

After you have pared the list down to mostly legitimate problems, you may wish to run a **Problem Facility Search.** This search will select all of the PES/ES building pair records in which the actual distance is less than the required distance, the computed maximum allowable NEW is less than the current sited NEW, or the building pair is waived or exempted. This produces a master list of all the potential problems, sorted by PES, that should be examined by the analyst.

Armed with a list of potential problems, the next step is to examine each by PES using the **PES/ES worksheet.** This is a spreadsheet-like screen which includes the Facility record data for the PES, and the PES/ES building pair data to each of the exposed sites. Changing a field like the PES's **Sited NEW** results in an immediate recalculation of required distances and maximum allowable NEW. The worksheet includes buttons for common preprogrammed searches, including special geometric searches for buildings with segmented clear zones, to reduce the PES/ES list to only those within a specified clear zone. There are also buttons and menu items for sorting, printing, performing user specified searches, and exporting the list to spreadsheets and other database programs.

When the analyst has a question about where a particular result came from, the **Detail Record** for that PES/ES pair is used. The Detail Record al-

lows the user to view most of the information about the PES, the ES, and their relationship on one screen. One button on this screen allows the user to review the criteria table data used in the computations, and to read any notes that are associated with the entry. If necessary, the computed results may be overridden and the record locked from future automatic updates.

Linking with the Map

All of the database screens described above include the capability to display the selected facilities on the map with the press of a button. This allows for better visualization of the problem, and provides a sanity check on the computer's calculations. In addition, buttons allow the user to select facilities on the map and display their database records. Therefore, the two-way link allows the database and map to act as if they were one program, while each maintains the capability to function separately.

One of the most important links between the database and the map is the capability to generate clear zones around selected facilities. Although it is possible to generate clear zones without the database, from within the map program itself, it is a cumbersome process when it involves multiple facilities of different types and net explosive weights. By using the database's searching and selecting capability, in combination with the built-in separation criteria tables, clear zones can be generated from each specified PES to a particular ES type. This allows the user to quickly determine where possible areas are for siting a new facility.

Choosing a Site for New Facilities

Once the candidate areas for the new site have been outlined by the clear zones of surrounding facilities, the user may create a new facility with the map template mechanism, choosing from any of the standard munitions enclosure types, and customizing it with dimensions from the "As-Built" drawings. A clear zone may also be grouped with the new building, if desired, and they can be rotated and moved to a position and orientation that fits. If multiple facilities are being sited, they can be created all at once, by specifying the number in each row and column, and their side-to-side and front-to-back separation distance.

After a site has been chosen and the new facilities have been placed, the procedure to compute distances and exposures can be invoked for the sur-

rounding facilities, and new records will be created in the database. After some additional information about the new facilities is entered, Air Force Form 943's may be printed for inclusion in a explosives site plan approval package.

Summing up the Capabilities

The hazard reduction and explosives site planning analysis capabilities of this software makes it possible for a person with the proper background and training to perform tasks at a speed and level of accuracy that would be impossible to accomplish by manual methods alone. The task, however, is still difficult, exacting, and time consuming, and human insight remains the ultimate quality control. Those of you who rely on your knowledge and experience in this area for a livelihood need have no fears of being replaced. Instead, look to the computer to supplement and focus your talents on areas where they be most productively applied, and to allow you the time to consider creative solutions by removing the burden of tedious measurements and calculation.